Superconducting Magnet R&D

Alexander Zlobin
Technical Division, Fermilab

Outline

Program goals
HFM technology development
Strand and cable R&D
LARP magnet R&D summary
Plans

Introduction/Conclusion

Fermilab's SC magnet R&D program addresses magnet issues important for Fermilab and for U.S. High Energy Physics

- **Support of Tevatron Collider operations**
  - **Study of present Tevatron magnets in order to improve machine performance (poster)**
  - **Development of special purpose magnets as required (e.g. short high strength dipoles, IR magnets for BTeV, etc.)**
- **Support of US participation in the LHC**
  - **Development and construction of 1st Generation IR Quads**
  - **Development of 2nd generation IR magnets for the LHC luminosity upgrade (LARP)**
- **Development of high field SC accelerator magnets and technologies for future HEP facilities (VLHC, LC, etc.)**

High Field Magnet Program Goals

HFM Program is focused on the development of next generation SC accelerator magnets with high operating fields (>10 T at 4.5 K) and large operating margins.

This Program was started in 1998 and originally driven by a VLHC needs, which determined main magnet parameters such as field range, aperture, magnet design, etc.

Since 2001 it is regarded as a generic base magnet R&D.

The specific feature of our program is that it focuses on practical magnet designs:

- **we worry about aperture and length, field quality, protection, manufacturability, cost, reproducibility, etc… not just peak field**

Superconductor and Technologies

SC Magnets at Fermilab

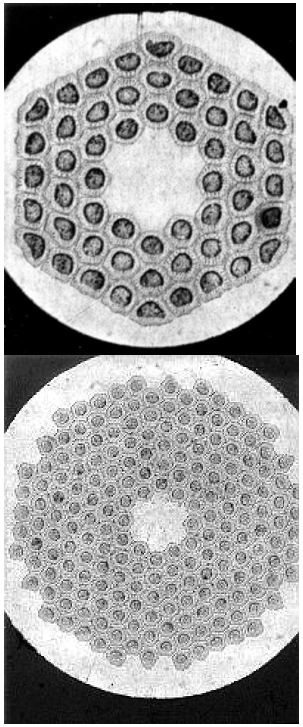
At the present time we develop accelerator magnets based on Nb_3Sn superconductor:

- **Critical parameters of Nb_3Sn (B_{c2}=27T, T_c=18K,and J_c(12T,4.2K)~2.5-3 kA/mm²) are much higher than NbTi parameters**
- **High-performance Nb_3Sn strands are commercially available in long lengths at affordable price**

We also keep an eye on other existing or new superconductors such as Nb_3Al, MgB_2, HTS, etc. which eventually may become potential candidates for accelerator magnets.

Since most of the new superconductors including Nb_3Sn are brittle => we need new magnet technologies for accelerator magnets based on brittle superconductors.

We explore two basic approaches: Wind-and-React and React-and-Wind.

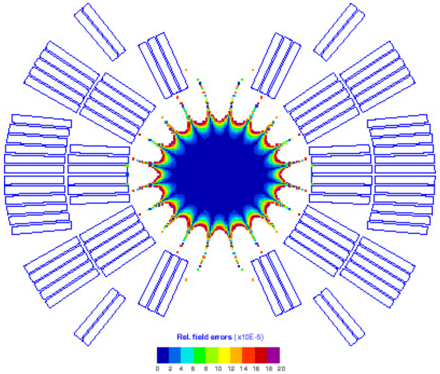


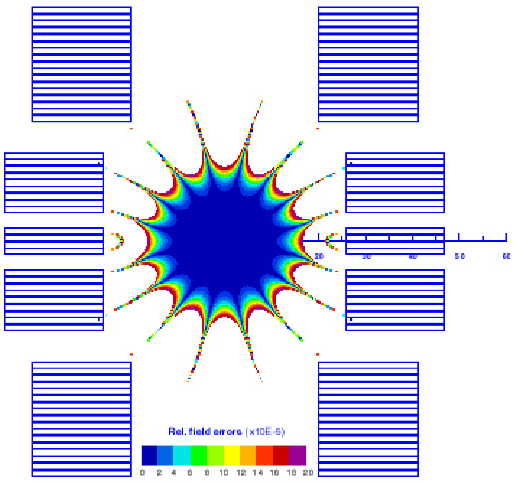
Nb3Sn strands produced using the Internal Tin and Powder-In-Tube technologies

Design Approaches

We are working with two basic dipole coil designs:

- ❖ **shell-type coils with a cos-theta azimuthal current distribution**
  - o **Traditional coil design for SC accelerator magnets, due to small bending radii requires W&R approach**
- ❖ **block-type coils arranged in the common coil configuration**
  - o **Friendly to brittle conductors thanks to large bending radii, allows R&W approach**





Both designs have advantages in different applications and both need to be studied and optimized.

Magnet R&D Infrastructure

Fermilab has the necessary infrastructure to perform successful magnet R&D including:

- **Cable insulating machine**
- **Winding tables (<2m,<15m)**
- **Coil HT oven and retorts (<1m)**
- **Epoxy impregnation facility (<6m)**
- **Collaring/yoking presses (<15m)**
- **Magnet test facilities (vertical <4m,horizontal <15m)**

The available infrastructure allows performing both *short and long* magnet R&D.

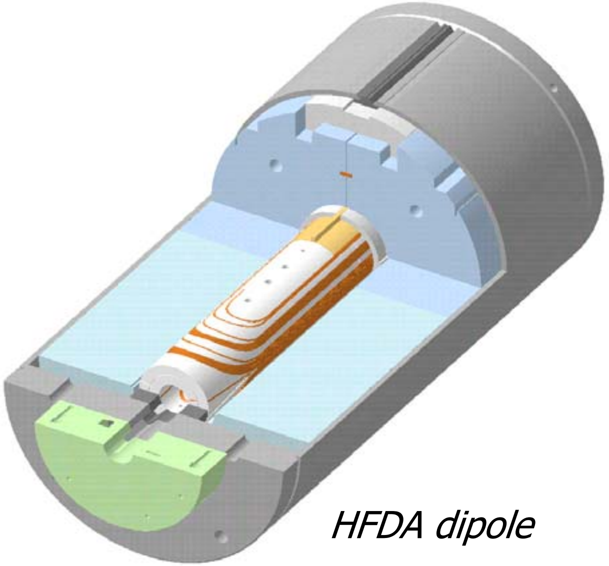
W&R Cos-Theta Dipole Models

SC Magnets
at Fermilab

The goal of this work is to develop 11 T Nb_3Sn accelerator quality magnets based on the W&R technique.

The main design features of our 1-m long cos-theta Nb_3Sn dipole models (HFDA) are:

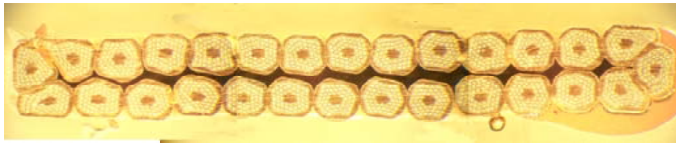
- **High-Jc 1-mm Nb_3Sn strand**
- **28 strand cable**
- **2-layer coil with cold iron yoke**
- **43.5-mm diameter bore**
- **Maximum field of 12 T at 4.5 K**



HFDA dipole

This design rests on the designs of the first Nb_3Sn dipole models developed in 1990s:

- **10 T dipole model (CERN/ELIN)**
- **11 T MSUT (Twente University)**
- **13 T D20 (LBNL)**



28-strand cable developed and fabricated at Fermilab

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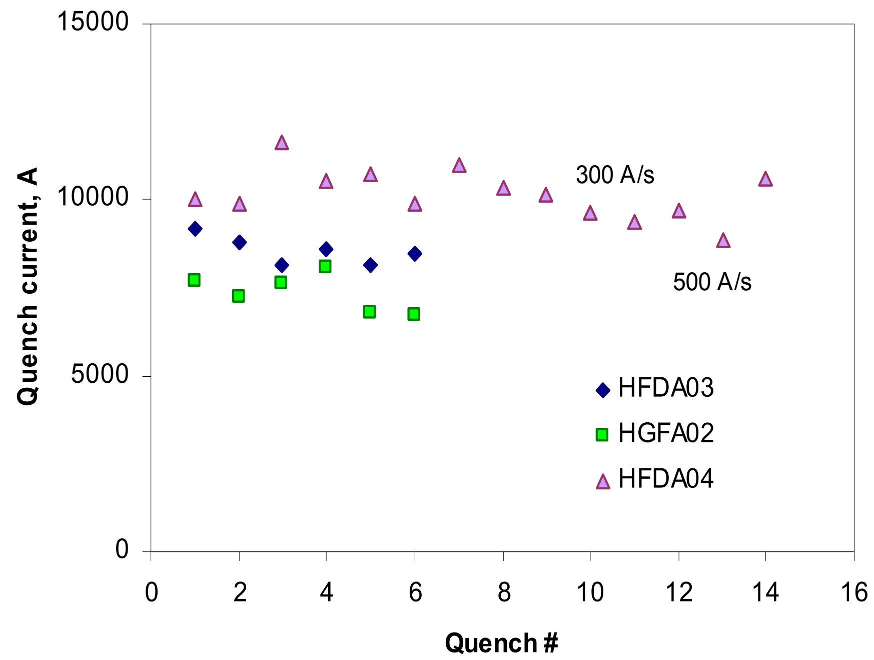
Cos-Theta Dipole Test Summary

Three short models (HFDA02-04) were fabricated and tested in FY2001-2002:

- **Good, well understood field quality including geometrical harmonics and coil magnetization effects**
  - **We developed and tested a simple and effective passive correction system to correct large coil magnetization effect in Nb_3Sn accelerator magnets**
- **Quench current was only 50-60% of expected short sample limit (B_{max}~6-7 T)**

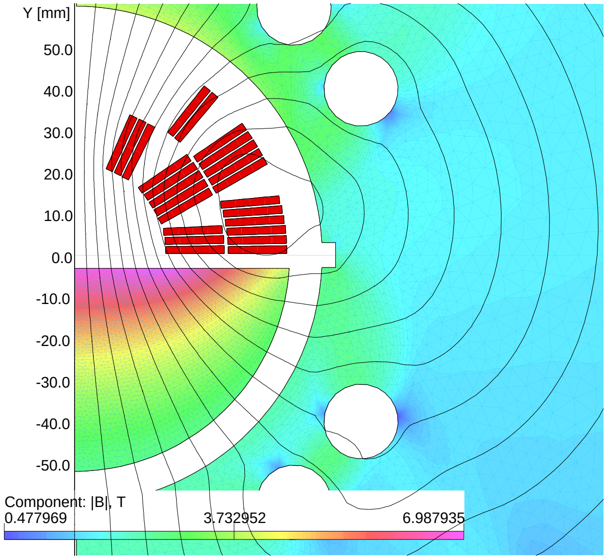


Quench performance of HFDA short models

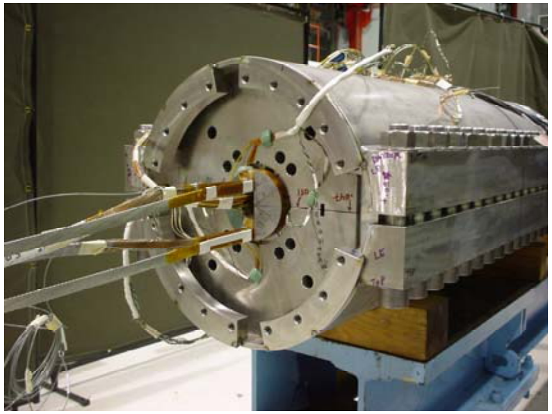
Magnetic Mirror

SC Magnets at Fermilab

- Since last year we have focused on understanding and improving magnet quench performance.
- We study and optimize the quench performance issues using half-coils and a magnetic mirror (**HFDM**).
- The main advantages of this approach are:
  - The same mechanical structure and assembly procedure
  - Advanced instrumentation
  - Shorter turnaround time
  - Lower cost



FNAL Magnetic mirror



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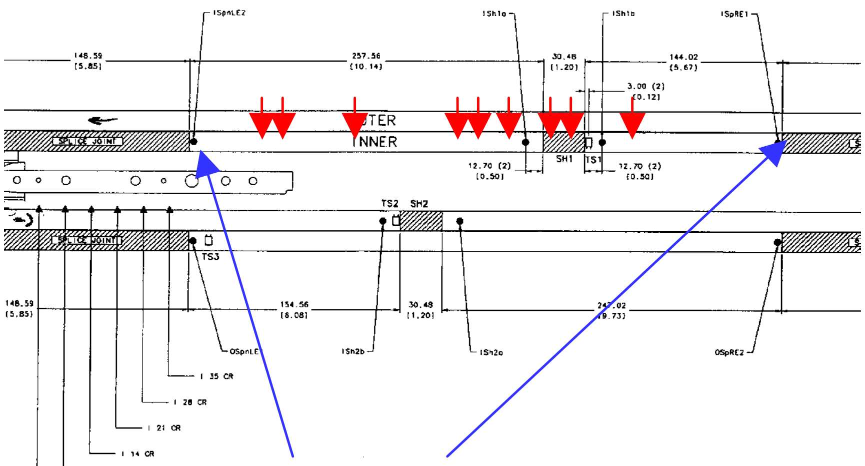
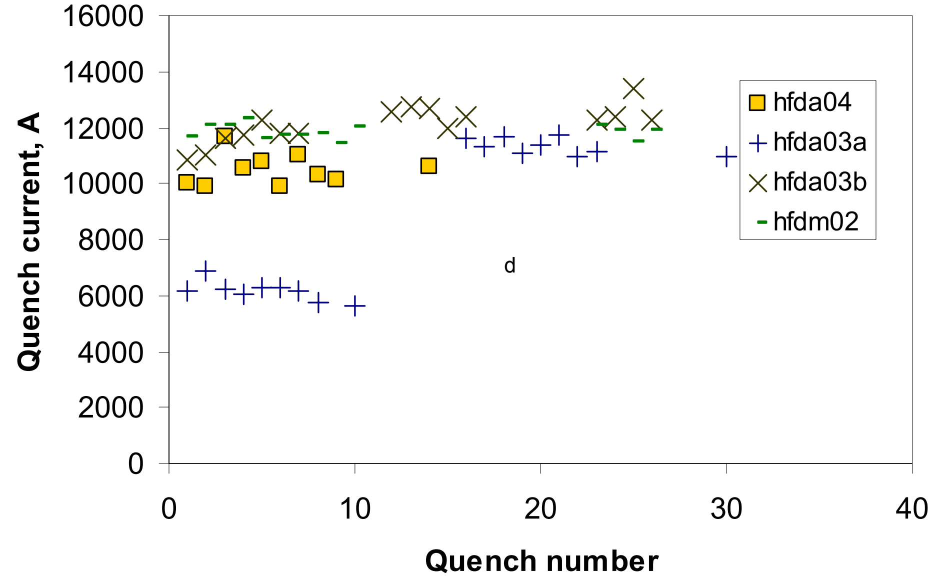
Mirror Magnet Tests

HFDA03b instrumentation and quench location



Cold quenches;
LHe bath temperature < 4.3K

Mirror magnet quench summary



Three mirror magnets HFDA03a, HFDA03b, and HFDM02 have been tested last year:

- **quench current was on the same level as in the dipole models**

Quench location, quench propagation velocity, critical current and temperature margin measurements point out on magnetic instability in Nb_3Sn strands at low fields.

Strand Instability Studies

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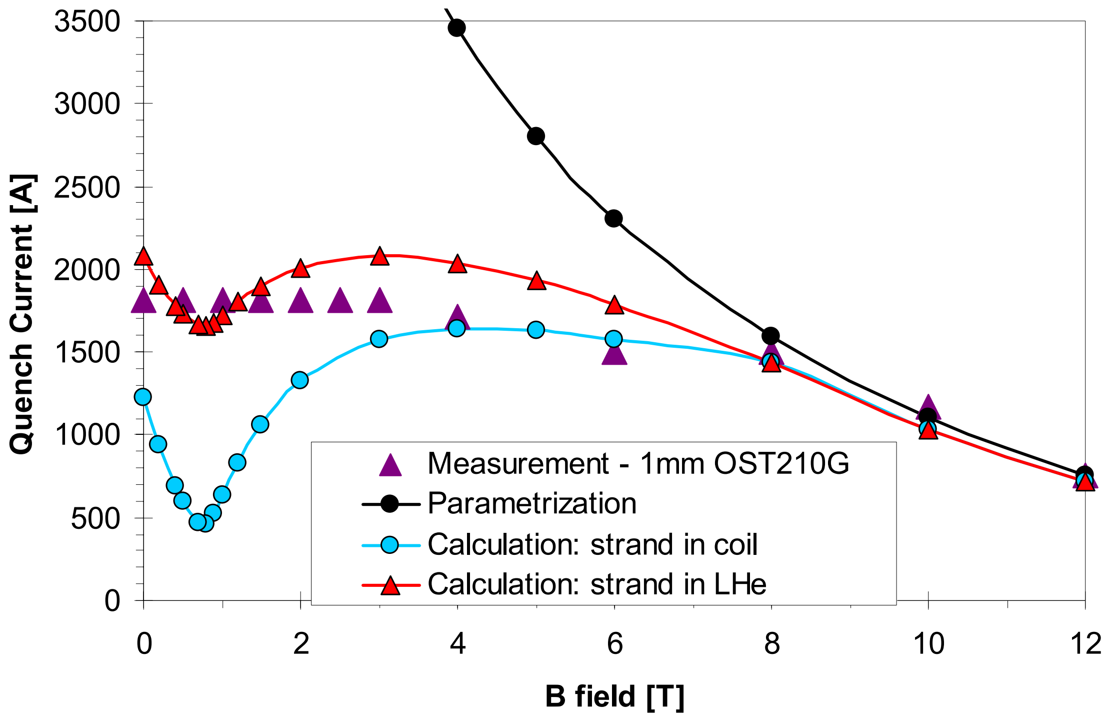
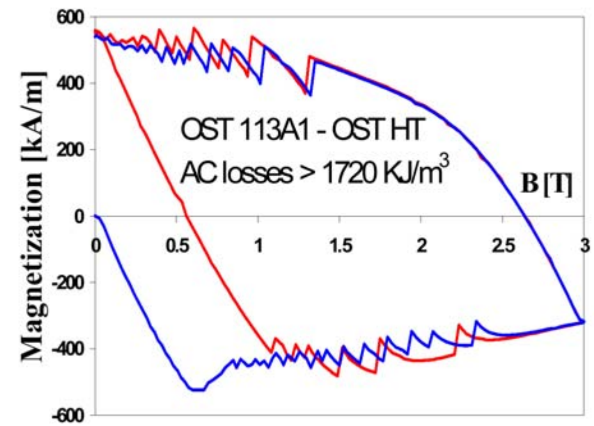
at Fermilab





Instabilities in strand quench current and magnetization

Strand quench current calculations and measurements revealed serious instability problems for the 1 mm MJR Nb_3Sn strand used in our cos-theta dipole models.

SC Magnets
at Fermilab

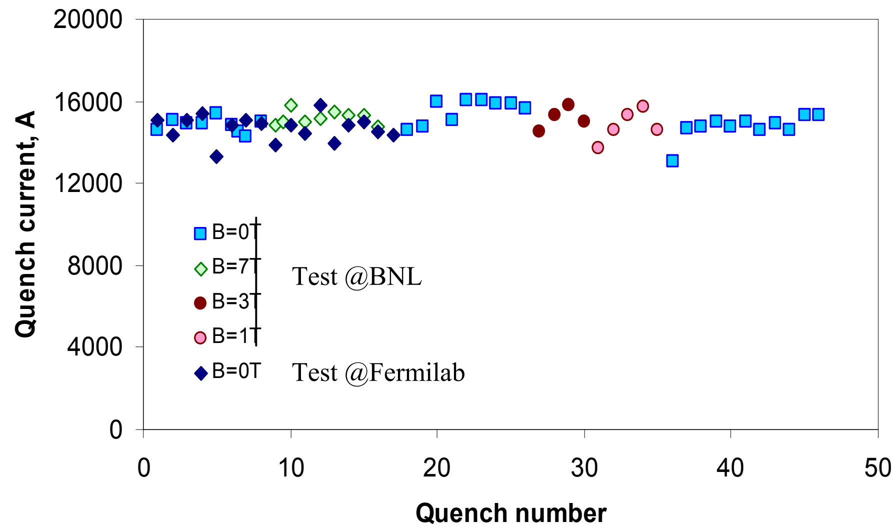
Cable Short Sample Tests

Cable test program has been launched last summer to address the conductor stability issues:

- **Fermilab: 23 kA SC Transformer, Bext=0T, T=1.9-4.2K**
- **BNL: 25 kA PS, Bext=0-7 T, T=4.3K**
- **CERN: 32 kA PS, Bext=0-10 T, P=0-100 MPa, T=1.8-4.2 K**

First results:

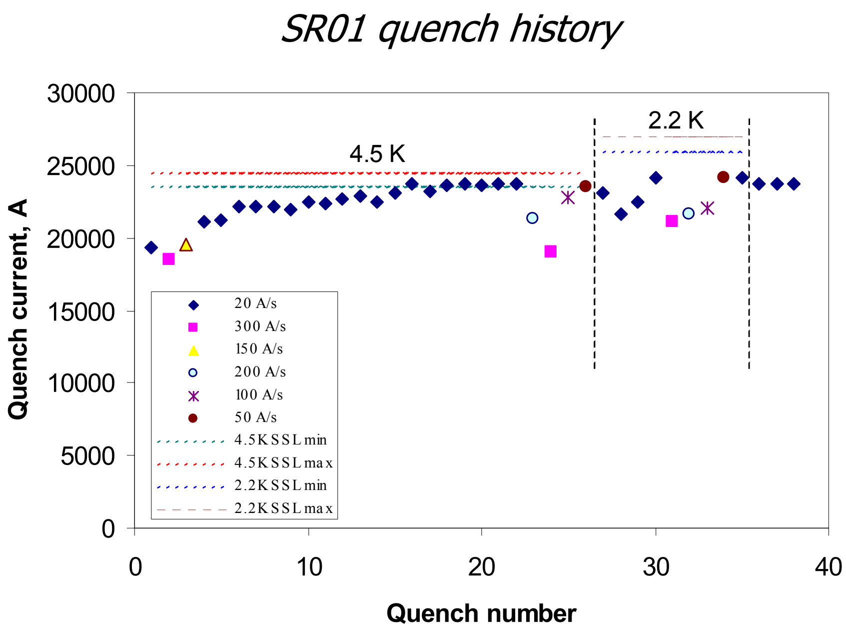
- **Good agreement of experimental data obtained at Fermilab and BNL on similar samples in similar test conditions**
- **The results are consistent with Fermilab's instability calculations and magnet test results**
- **These studies will be continued**

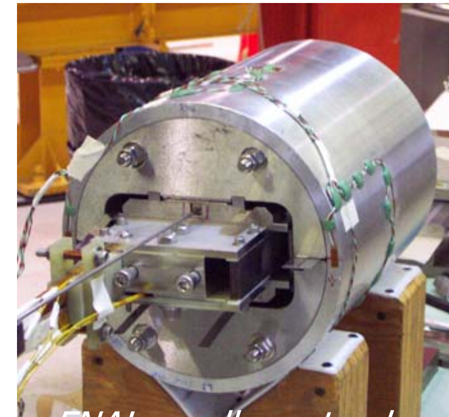


28 strand MJR-1.0mm cable tested at BNL and Fermilab

SC Magnets
at Fermilab

Small Racetracks





- **We also started testing cables at Fermilab using small racetrack coils:**
  - **Use simple reliable mechanical structure developed at LBNL**
  - **Coil design was modified to test real full-size cables in real conditions**
- **1st (PIT1.0) Fermilab racetrack: tested in January-March 2004**
  - **Racetrack SR01 reached the short sample limit @4.5K (see quench history)**
  - **PIT1.0 cable is quite stable and can be used in model magnets**
- **We will continue testing Nb_3Sn cables with small racetracks before using them in real magnets.**

SC Magnets
at Fermilab

Cos-theta Models

Mirror configuration HFDM03:

- o PIT 1mm cable
- o Optimized pre-stress
- o Advanced instrumentation

❖ Fabrication has been completed last week

❖ Test is scheduled for April.

❖ Goals:

- o Reach 10 T field level
- o Test mechanical structure at high fields

HFDM03 cold mass

Next steps:

❖ Dipole model HFDA05 (June 2004):

- o 28-strand PIT 1mm cable (coil from HFDM03 + new half-coil)

❖ Dipole model HFDA06 (October 2004):

- o 28-strand PIT 1mm cable (two new half-coils)

W&R Summary

- **Progress in understanding of the quench performance limitations was made:**
  - **Nb_3Sn strand magnetic instabilities cause premature magnet quenches.**

- **To improve magnet quench performance we plan:**
  - **Continuation of cable short sample testing at Fermilab, BNL, and CERN and cable testing with small racetracks**
  - **Testing RRP and MJR 0.7mm strands and cables and use them in cos-theta models**
    - **Coil x-section for 0.7 mm strand has been modified**

React & Wind Technology

Last year we accomplished the first phase of R&W technology study. The goals of this work were to study the possibilities and limitations of the R&W approach for Nb_3Sn magnets and develop a 10 T accelerator quality common coil dipole magnet based on this approach.

Experimental studies and optimization of R&W techniques were performed using 1-m long racetrack coils (HFDB):

- **sub-sized 41-strand cable**
- **simple coil geometry: two flat racetrack coils separated by 5 mm gap**
- **simple bolted mechanical structure**
- **maximum field 11 T**

Three R&W racetracks have been fabricated and tested in FY2001-2003:

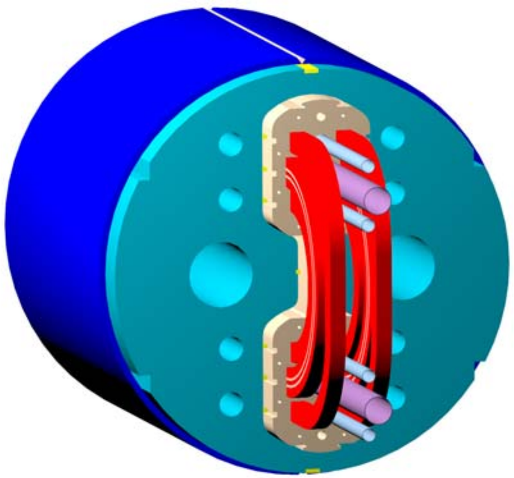
- **2^{nd} and 3^{rd} racetracks reached 75-78% of their short sample limit**

FNAL R&W racetrack

R&W Common Coil Dipole

We developed common coil dipole model (HFDC) which meets accelerator magnet requirements:

- High-J_c 0.7 mm Nb_3Sn strand
- Wide 60-strand cable
- Single-layer coil with cold iron yoke
- Advanced mechanical structure
- Magnet bore of 40 mm
- Nominal field of 10 T at 4.5 K

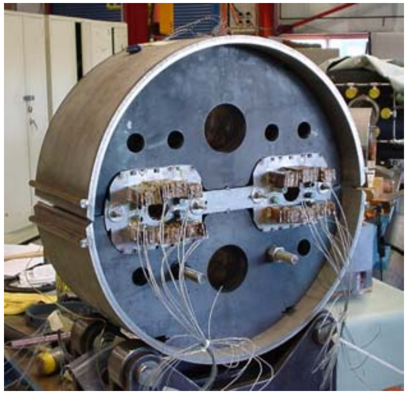


FNAL Common coil dipole

Mechanical and technological models were fabricated and tested in FY2002.

The 1st common coil short model has been fabricated and tested in September, 2003:

- Good, well understood field quality
- Long training, ~75% of quenches occurred in one of two coils
- Max quench current reached 60% of the short sample limit



Mechanical model

R&W Summary

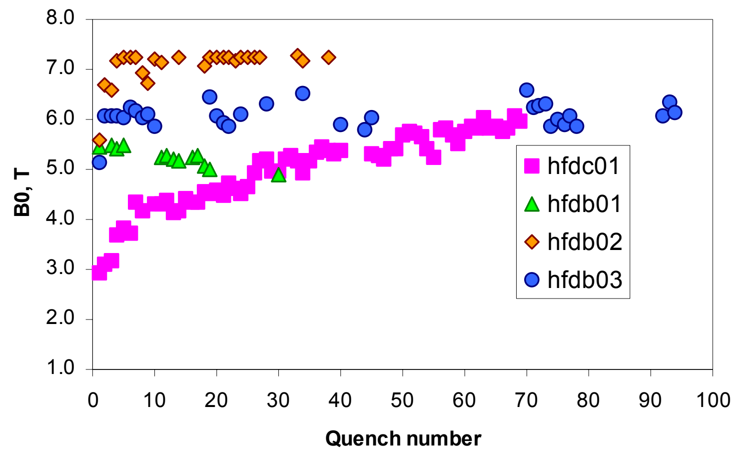
SC Magnets
at Fermilab

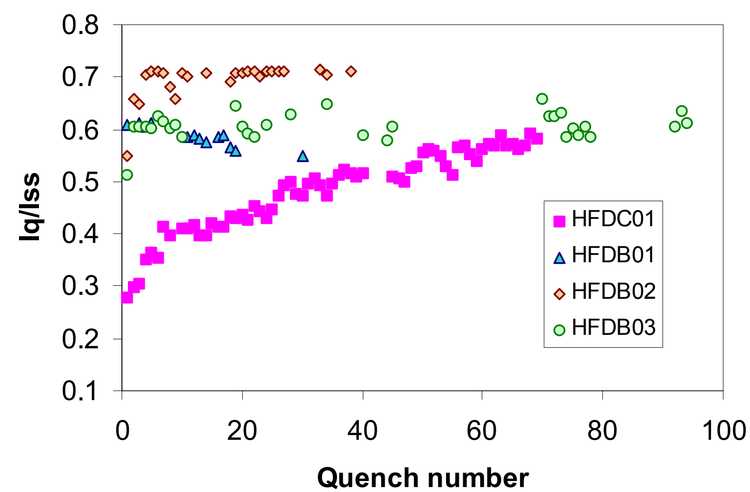
Four 1-m long magnets based on reacted Nb_3Sn cable were fabricated and tested:

- **All magnets survived the complicate fabrication process and reached 60-70% of the Short Sample Limit.**
- **The critical current degradation of reacted cable was much larger than expected due to:**
  - ✓**Nb3Sn conductor limitations**
  - ✓**Magnet mechanics**

To use the R&W approach in accelerator magnets both the conductor and the magnet technology have to be improved.

We will focus on the conductor studies and improvements.



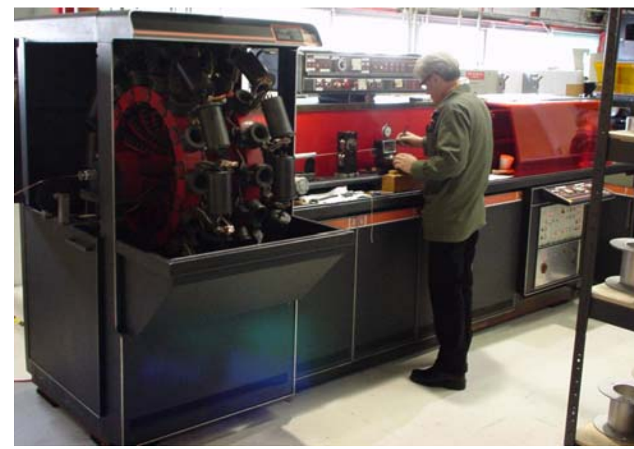


Quench performance of R&W magnets

Material and Component R&D

- **New generation accelerator magnets require advanced superconductors, structural materials and components.**
- **Fermilab developed an infrastructure to perform extensive material R&D in support of the magnet R&D programs:**

  - **Ovens for Nb_3Sn Heat Treatment**
  - **Compact 28-strand cabling machine**
  - **Sample compression fixtures**
  - **Ic and M measurement equipment**
  - **Compact 25 kA SC transformer**
  - **SEM and optical microscopes**
  - **Short Sample Test Facility**
    - **15-17 T solenoid,**
    - **1.5-100 K temperature insert**



- **We are participating in National Conductor and Material Development Programs sponsored by DOE.**

Nb_3Sn Strand R&D

SC Magnets at Fermilab

We study 0.3-1.0 mm Nb_3Sn strands produced using different methods:

- **"Internal Tin" (IT, RRP)**
- **"Distributed Tin" (DT)**
- **"Modified Jelly Roll" (MJR)**
- **"Powder in Tube" (PIT)**

Strand studies include:

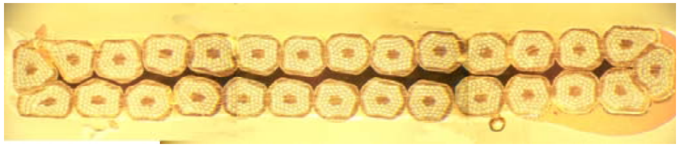
- **$I_c(B)/J_c(B)$** ⇒ **magnet short sample limit**
- **RRR** ⇒ **quench protection**
- **M(B)** ⇒ **field quality @ low fields**
- **magnetic instabilities** ⇒ **max quench current**
- **SEM studies & chemical analysis**
- **Strand expansion after HT** ⇒ **technology**
- **Heat treatment optimization**

An example of our recent studies of strand stability is shown on slide #11 (more details in HFM poster).

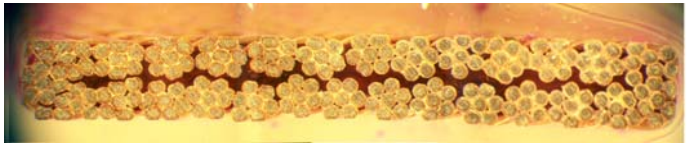
Cable Development

We develop and fabricate Rutherford-type cables:

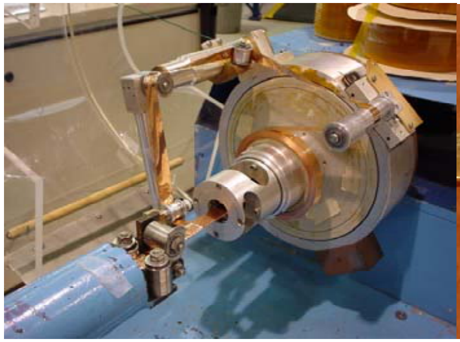
- **Different Nb_3Sn strand types**
- **Rectangular and keystone x-section**
- **With and w/o resistive core**
- **Different packing factor**
- **One and two-stage cables**
- **Copper stabilizer**
  - **Cu tape wrapped on the cable**

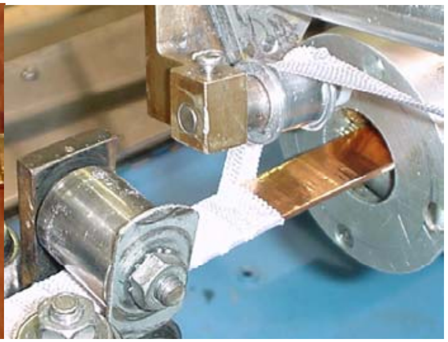


28-strand one-stage cable (FNAL)



28-strand two-stage cable (FNAL)





25 micron Cu tape (stabilizer) was wrapped around the cable using cable insulating machine.

Cable Studies

SC Magnets
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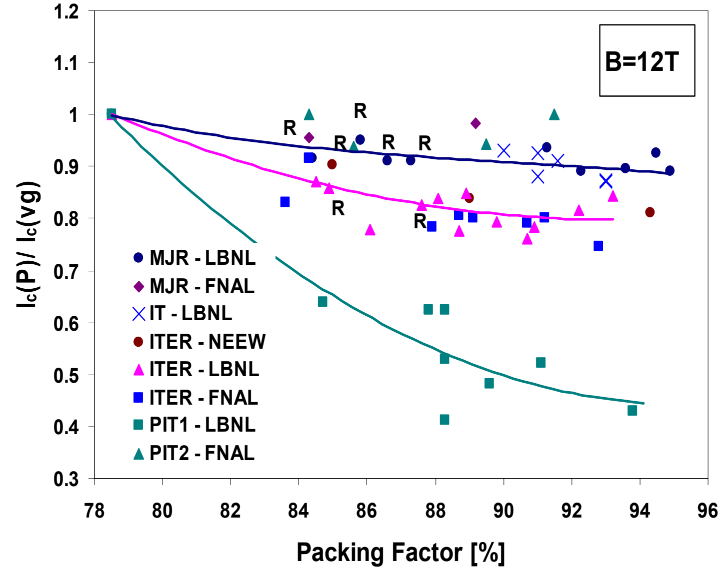
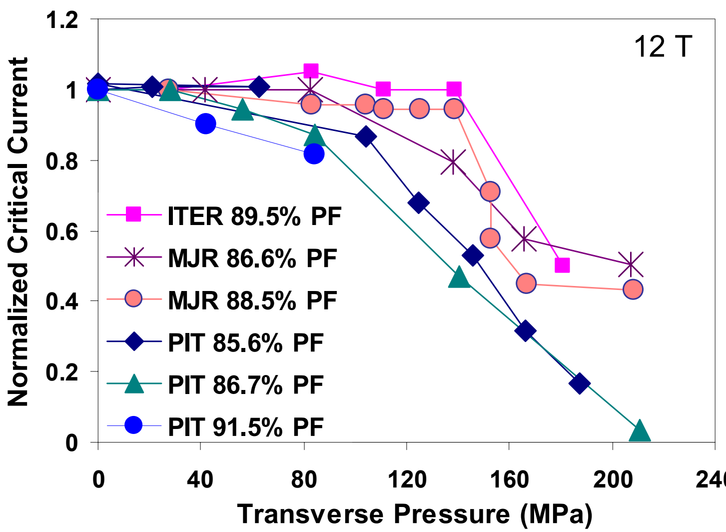
Cable studies include:

- ❖ I_c degradation due to
  - o **cabling**
  - o **bending**
  - o **compression**
  - o **instabilities (slide #12)**
- ❖ cable inter-strand resistance



Ic degradation of different Nb_3Sn strands during cabling vs. cable cross-section and packing factor.



I_c degradation of different Nb_3Sn strands inside cable vs. transverse pressure applied to the cable.

LARP magnet R&D

- **Fermilab is responsible for the development of new generation IR quads for the future LHC luminosity upgrade**
- **FY04 plan:**
  - **IR quadrupole conceptual design studies and technology development**
  - **preparation to short model R&D at Fermilab**
- **Major studies and results (details in the HFM poster):**
  - **Aperture limitation studies**
  - **Analysis and comparison of block-type and shell-type quad designs**
  - **Analysis of the double-aperture quadrupoles**
  - **Evaluation of different mechanical structures for large-aperture Nb_3Sn quads**
  - **Thermal analysis of IR Nb_3Sn dipole and quarupole**
  - **Development of a conceptual design of the first quadrupole short model**

Long-term Plan

- **In FY04-FY05 we are planning production and test of 2-3 Nb_3Sn model magnets per year.**
  - **The goals are to understand and improve the magnet technologies and quench performance, and optimize the field quality.**
- **In FY06 we will start testing first LARP short quadrupole model.**
- **When basic problems are understood, we plan to increase the production and tests of HFM models of different types (including models for LARP) to 5-6 per year.**
  - **The goal is to study and optimize the performance reproducibility and magnet cost.**
- **Assuming that short model R&D is successful we could start developing infrastructure for long models in FY2006-2007 and start long coil testing in FY2007.**